Micro-Packaging of MEMS Sensor Suites for Remote Health-Monitoring Systems

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Outline

- Introduction
- Project Goals
- System Requirements
- Sensor Search
- Sensor Packaging
- Environmental Monitoring System
- Further Miniaturization
- Status/Future Work

Introduction

- The U.S. Army is currently developing a missile diagnostic and prognostic monitoring system, RRAPDS (Remote Readiness Asset Prognostic/Diagnostic System).
- The system requires miniature, reliable, modular, and inexpensive environmental sensor suites.
- MEMS-based environmental sensors are beginning to emerge in the marketplace, but have not been inserted into fielded missiles or munitions.
- For many of these sensors, and other MEMS-based devices, a significant factor in the sensor reliability and cost is the packaging and integration.
- This program is developing packaging and integration options for miniature sensor suite fabrication and insertion.

Remote Readiness Asset Prognostic/Diagnostic System

- **Sense multiple variables**
- **Sense 10% beyond mil-spec**

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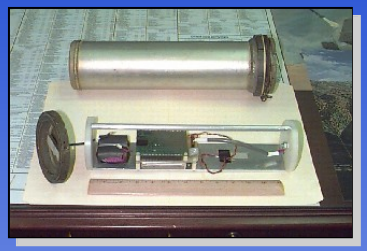
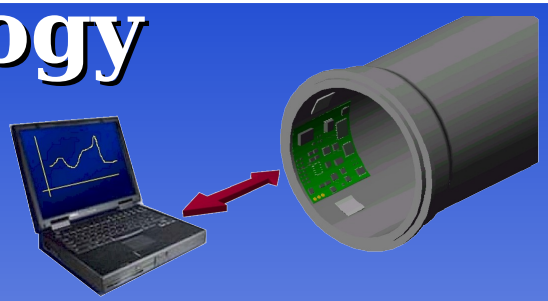
MEMS = Enabling Technology

From this...





To this...

Current Missile Health Monitoring System

Projected MEMS-Based System

MEMS offers THE potential solution to size, weight, power, and cost issues for environmental conditions monitoring

- **Military Assets Health & Readiness Monitoring**
- **Shipping & Transportation/Perishables Monitoring**
- **Forward Reconnaissance & Surveillance**
  - **Weather Conditions**
  - **Seismic Conditions**
  - **Chemical Agents Detection**

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Projected RRAPDS Capabilities

- Will measure and record:
  - Shock/Acceleration: +/- 200 g's in 3-axes
  - Temperature: -55°C to 125°C
  - Humidity: 0-100% RH
  - Chemicals: Fuels, Explosives, Coolants, NaCl, etc.
- Will have minimal impact on the system being monitored.
- Will be modular and reconfigurable for application to different army systems.
- May be conformal to the system structures.
- Have a 10 year maintenance-free data storage capability and system lifetime.
- Be reliable through military environmental conditions.

RRAPDS Sensor Suite Requirements

- Shock/Acceleration, Temperature, Humidity are the first sensor types required. Chemical concentrations, currents, electromagnetic fields required later.
- Must operate using 3.3V or less power supplies.
- Must survive **and remain operational** through all environmental specifications on missile storage and operation.
- Must be reconfigurable, with “plug-and-play” miniature components.
- Must have quiescent current on the order of microAmps.
- Signal conditioning is included in the sensor, and must be scaled for compatibility with A/D convertors

Project Goals

- Select the sensors, signal conditioning electronics, and data processing/storage components required to assemble a miniature sensor suite meeting RRAPDS requirements.
- Develop standardizable and modular processes for integrating either packaged MEMS devices, or unpackaged MEMS die, onto laminate PCBs with standard SMT electronics.
- Develop novel chip-on-board and flip-chip-carrier MEMS packaging techniques to enhance current sensor suite manufacturing processes.
- Develop a low-cost environmental monitoring system using commercially available MEMS sensors, new packaging schemes, and modular integration techniques.
- Investigate the robustness and survivability of microsensor packages in harsh environments using environmental cycling and accelerated aging.

Sensor Search

Vibration/Shock (Accelerometers)			
CompanyName	**Size**	**Packaging**	**Cost**
Analog Devices, Inc.	Large	Packaged	Medium
Auburn University	Small	Custom	R & D Stage
Carnegie Mellon University	Small	Custom	R & D Stage
CSEM	Large	Packaged	High
E G & G	Medium	Packaged	Medium
Endevco, Corp.	Small	Packaged	High
IC Sensors	Medium	Packaged	Medium
Instrumented Sensor Technology, Inc.	Medium	Packaged	High
Measurement Specialties, Inc.	Small	Packaged	Medium
Motorola	Medium	Packaged	High
Silicon Designs, Inc.	Medium	Packaged	High
TEMIC TELEFUNKEN	Medium	Packaged	High
University of Michigan	Small	Custom	R & D Stage
Weld Star, Inc.	Large	Packaged	High
Wilcoxon, Inc.	Small	Custom	R & D Stage

Temperature Sensors			
CompanyName	**Size**	**Packaging**	**Cost**
Analog Devices, Inc.	Small	Packaged	Low
Alpha Semiconductor, Inc.	Medium	Packaged	Medium
Sensor Scientific, Inc.	Medium	Packaged	Medium
Dallas Semiconductor Corp.	Small	Packaged	Low
National Semiconductor	Medium	Packaged	Medium
HL Planartechnik	Large	Packaged	High
Goodyear	Large	Packaged	High
Sensor Scientific, Inc.	Medium	Packaged	High
Weld Star, Inc.	Large	Packaged	High
Ultrafast Sensors & Applications	Small	Packaged	High

Humidity Sensors			
CompanyName	**Size**	**Packaging**	**Cost**
Hart Scientific	Large	Packaged	High
Testo	Large	Packaged	Medium
Rel-Tek	Large	Packaged	Medium
AWS	Large	Packaged	Medium
Building Automation Products	Large	Packaged	Medium
Rotronic Instrument Corp.	Large	Packaged	Medium
Campbell Scientific Corp.	Large	Packaged	Medium
General Eastern Instrument	Medium	Packaged	Medium
SMARTEC	Large	Packaged	Medium
Phillips	Large	Packaged	Medium
Ohmic Instrument Co.	Medium	Packaged	Medium
Honeywell	Large	Packaged	High
Elan Technical Corp.	Medium	Packaged	High
Hygrometrix, Inc.	Medium	Packaged	High
Hygrometrix, Inc.	Small	Custom	Medium
Rotronic Instrument Corp.	Large	Packaged	Medium
Panametrics, PCI	Medium	Packaged	High
Weld Star, Inc.	Large	Packaged	Medium

Sensor Specification Ranges

Accelerometer Specification	Minimum	Average	Maximum
Resolution	1 μg	-	1mg
Range	2g	-	1000g
Min Operating Temperature	-55°C	-40°C	0°C
Max Operating Temperature	70°C	85°C	125°C
Min Storage Temperature	-73°C	-65°C	-40°C
Max Storage Temperature	90°C	130°C	150°C

Accelerometers

- Most sensor performance requirements can be met with existing technologies.
- Many power requirements cannot be met by existing devices.
- Sensor size and packaging is not addressable

Temperature Sensors

- Most sensor performance requirements can be met with existing technologies.
- Power, size, and packaging requirements can also be met

Temp. Sensor Specification	Minimum	Average	Maximum
Resolution	0.1°C	1°C	2°C
Maximum Temperature	100°C	150°C	302°C
Minimum Temperature	-67°C	-55°C	-20°C
Min Storage Temperature	-85°C	-55°C	-40°C
Max Storage Temperature	90°C	155°C	311°C

Humidity Sensor Specification	Minimum	Average	Maximum
Resolution	-	2%RH	-
Range	-	100%RH	-
Min Operating Temperature	-50°C	-40°C	-20°C
Max Operating Temperature	50°C	85°C	190°C
Min Storage Temperature	-	-	-
Max Storage Temperature	-	-	-

Humidity Sensors

- Some sensor performance requirements can be met with existing technologies.
- Few sensors meet power requirements
- Packaging for exposed MEMS sensors is not mature
- Long-term reliability of MEMS and especially exposed MEMS has not been studied

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Sensor Search Summary

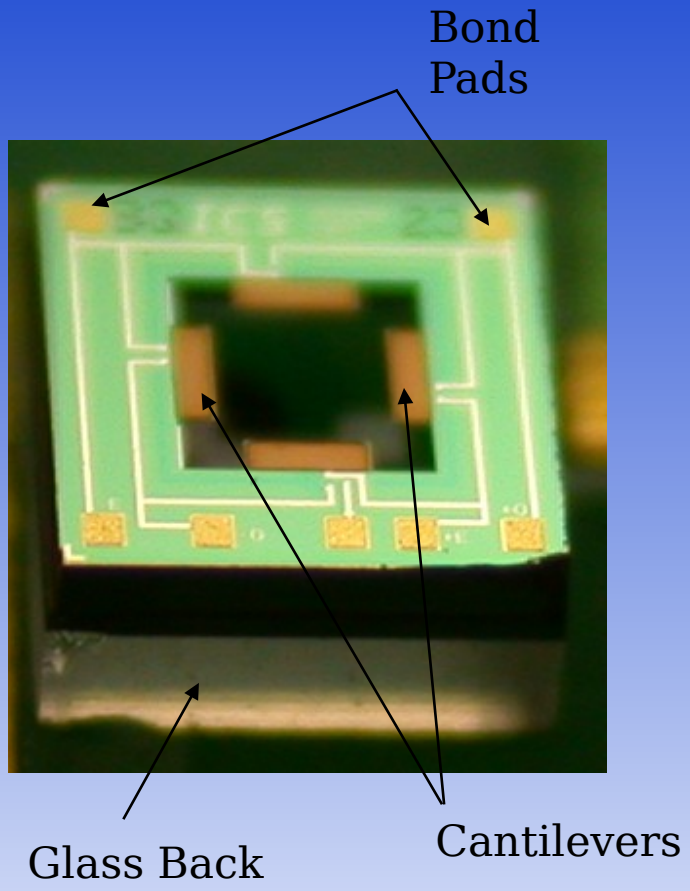
	Availability	Size	Packaging	Cost
Temperature Sensors	High	Small - Mediium	No Problem	Low - Medium
Humidity Sensors	Low	Medium - Large	Problematic	Medium - High
Accelerometers	Medium	Medium - Large	Problematic	Medium - High

- **Temperature Sensors:**
  - Easiest to find and readily available.
  - Many different vendors and packages to choose from.
- **Accelerometers:**
  - Difficult to obtain devices meeting all requirements.
  - Size and packaging styles were primary factors which limited this search.
  - Ultimately, size constraints lead to custom packaging of the Wilcoxon Research Accelerometer chosen for this effort, and integration of an Endevco PicoCHIP device.
- **Humidity Sensors:**
  - Most difficult to find.
  - Packaging was a key factor which lead to custom package development for the Hygrometrix HMX2000 humidity sensor die chosen for this effort.

Sensor Chip-Scale Packaging Objectives

- Accelerometer
  - Develop an extremely low-profile package.
  - Keep packaging and integration costs low.
  - Protect sensing element and microstructures.
  - Demonstrate highly reliable devices and high yield processes.
- Humidity/Chemical Sensors
  - Develop an extremely low-profile chip-scale package.
  - Keep packaging, integration, and support costs low.
  - Protect the metallization and the interconnect from the environment.
  - Simultaneously allow exposure of sensing element to the environment.

Hygrometrix Humidity Sensor



- Humidity develops stress in a set of micromachined cantilever beams.
- Piezoresistive bridge converts strain to voltage.
- On-chip temperature sensor also available.

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Initial Integration Process Flow

Obtain bare sensor die.

Stud bump gold balls onto die.

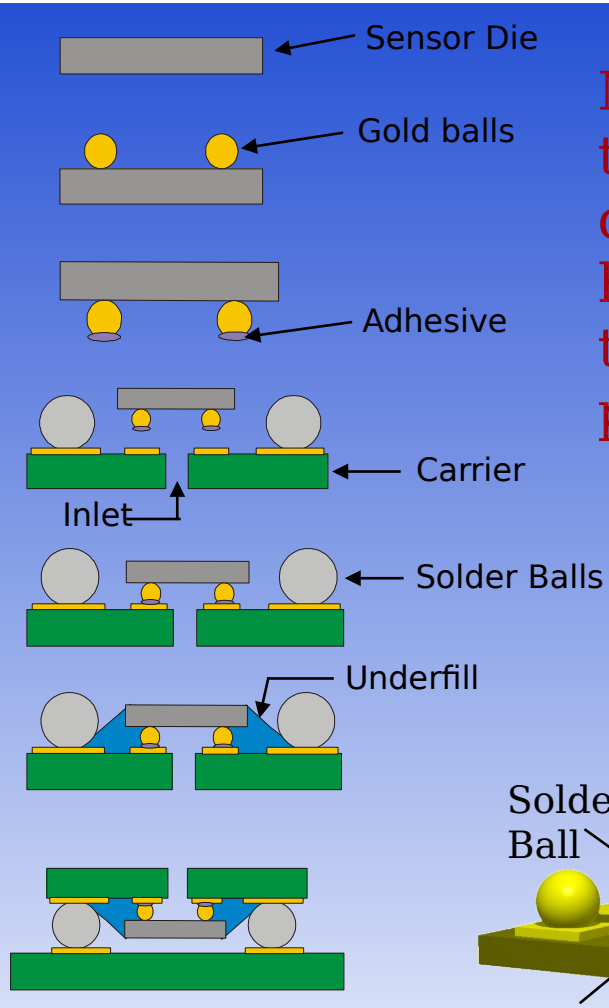
Dip gold balls into conductive epoxy.

Flip die onto a carrier PCB with attached solder balls.

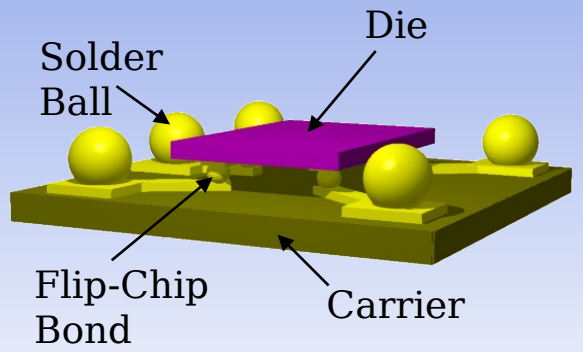
Cure the epoxy, bonding the die to the carrier PCB.

Perform partial underfill for added ruggedness and reliability.

Flip the complete package onto the laminate PWB and reflow solder.



New vacuum tooling developed to handle die during the assembly process.



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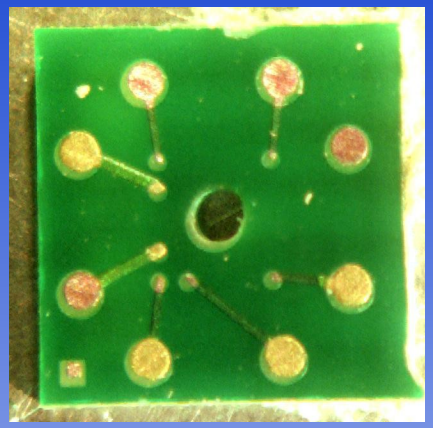
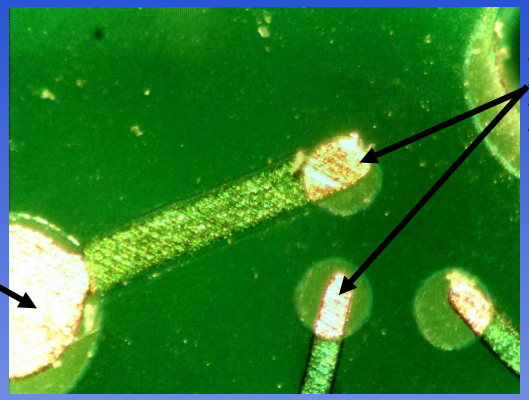
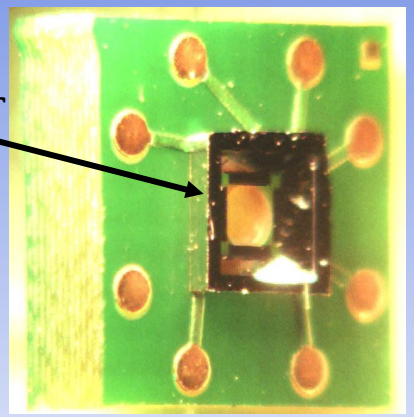
Humidity Sensor Carrier



Humidity Sensor FR4 Carrier



Close-up of Metallization



Carrier with
Attached Sensor

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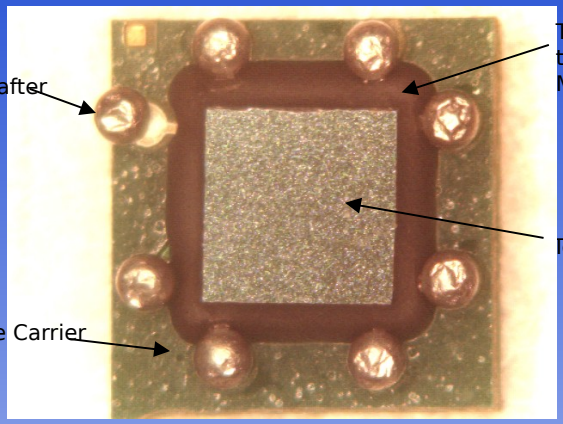
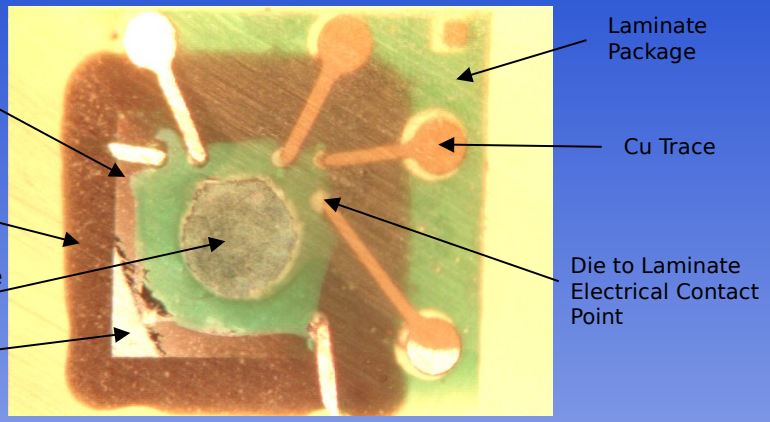
Packaged Hygrometrix Test Die

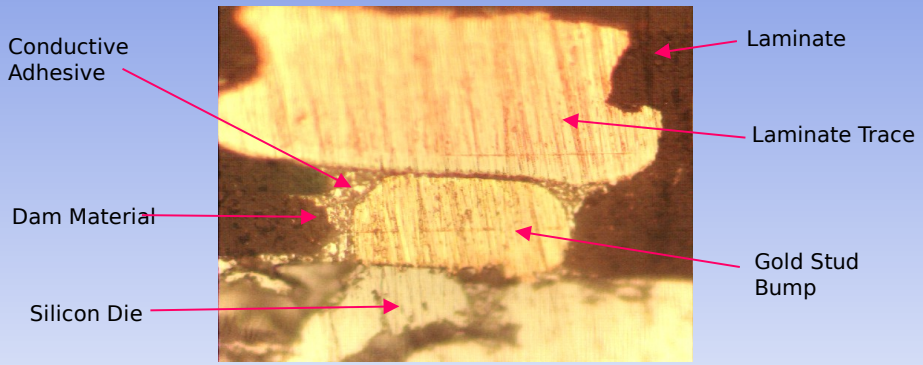
Packaged Hygrometrix Test Die with attached SnPb Solder Balls



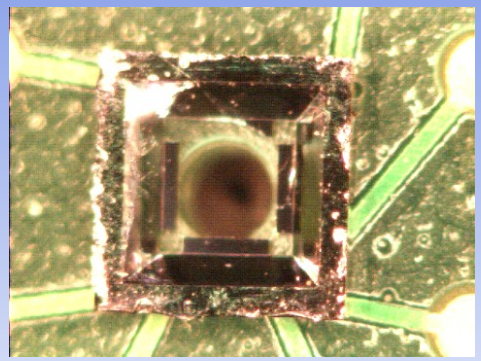
Polished Hygrometrix Test Die Showing Extent of Dam Material Underflow



Cross-Sectioned Hygrometrix Test Die



Real Hygrometrix Die on Laminate Carrier (Unattached)



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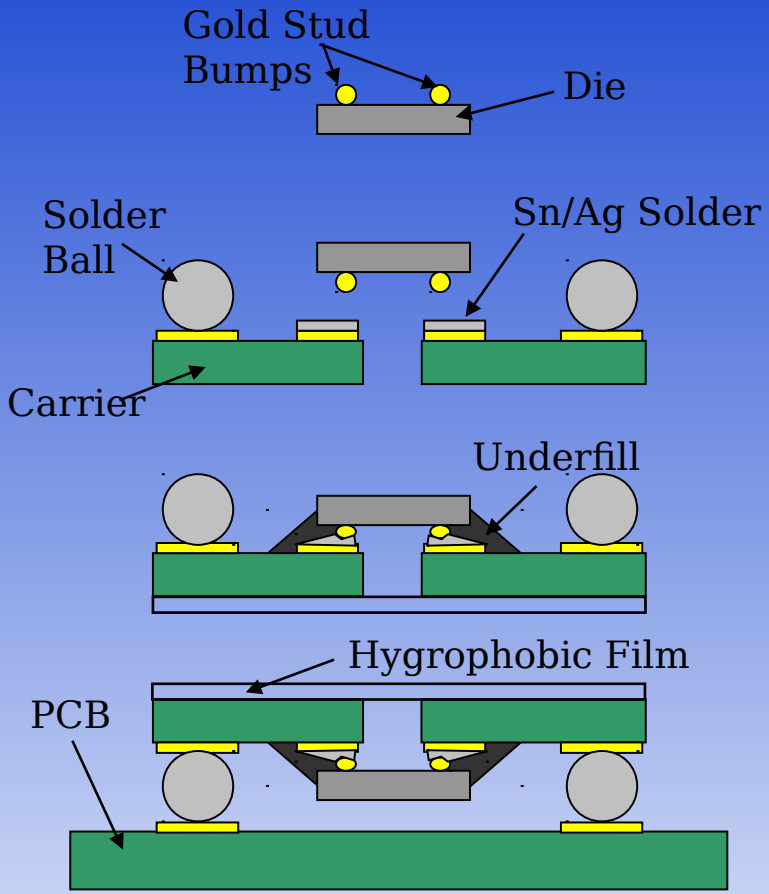
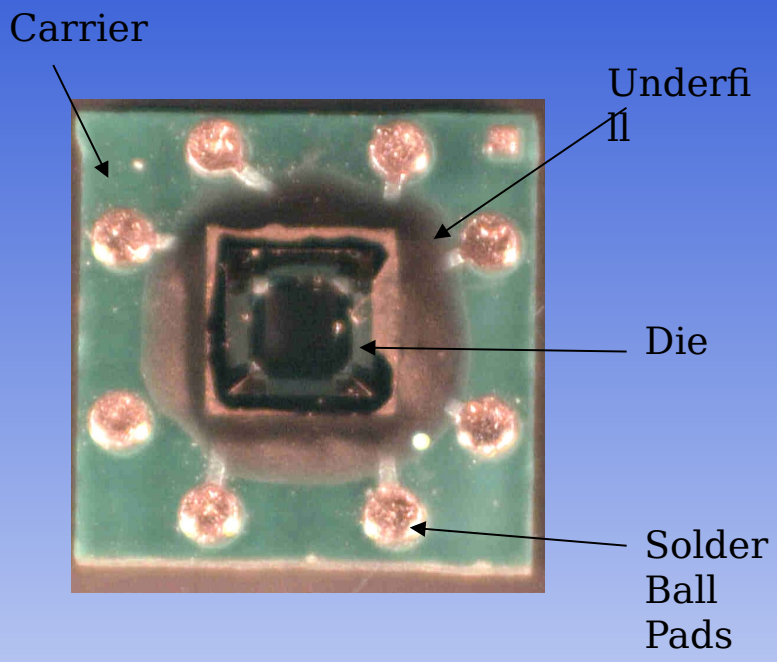
Modified Process Flow



1. Using a gold ball bonder, place gold stud bumps onto sensor die
2. Flip and align die to a Sn/Ag coated carrier. Bonding is performed in a thermocompression bonder, but the bond is developed through the formation of a eutectic between gold ball and solder.
3. Apply underfill around sensor die and cure. Porous hygrophobic film attached.
4. Align packaged device with site on printed circuit board and reflow along with other SMT microelectronics.

Final Packaged Die

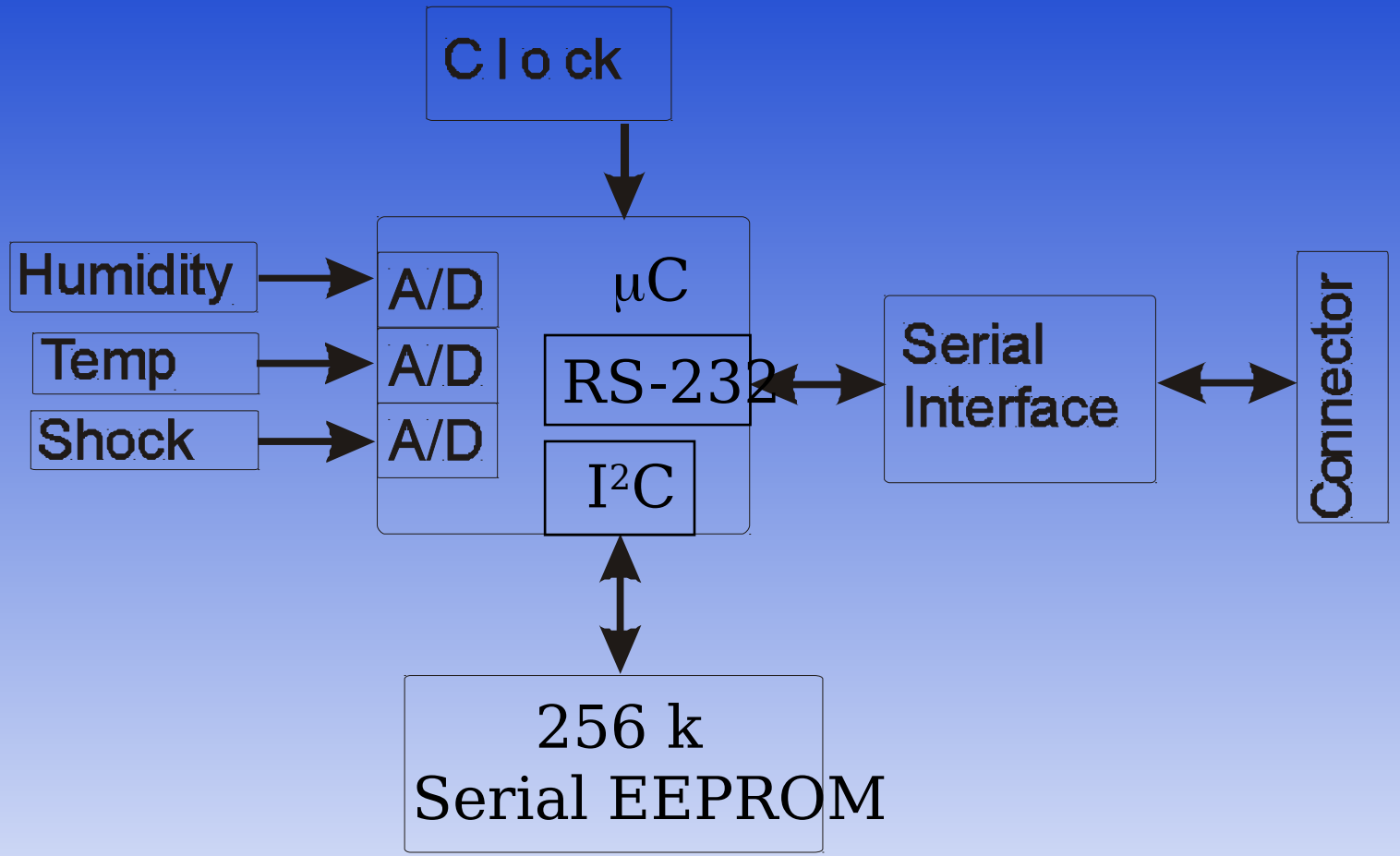


- Laminate carrier (ceramic carriers have also been made).
- Flip-chipped humidity sensor die onto carrier.
- Humidity sensor underfilled to improve thermal, mechanical, and humid environment reliability.
- Integration on printed circuit boards using standard solder ball reflow.

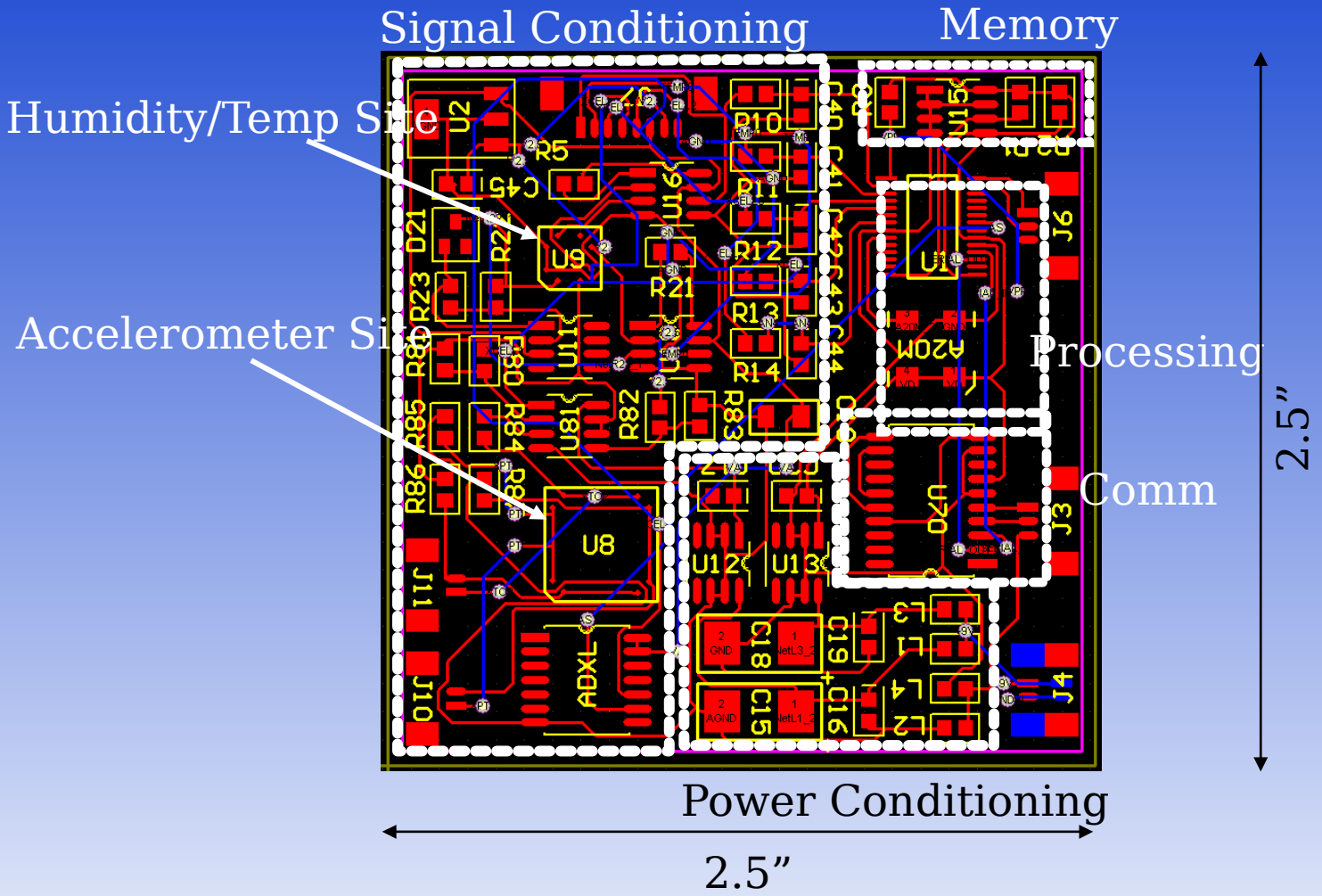
Environmental Monitoring System Objectives

- Serve as a testbed for the integration and test of newly packaged MEMS devices.
- Collect data from baseline packaged COTS sensor devices.
- Enable parallel data acquisition and storage during environmental cycling.
- Serve as a demonstration unit for MEMS packaging and system miniaturization efforts.

Monitoring System Block Diagram



System Layout



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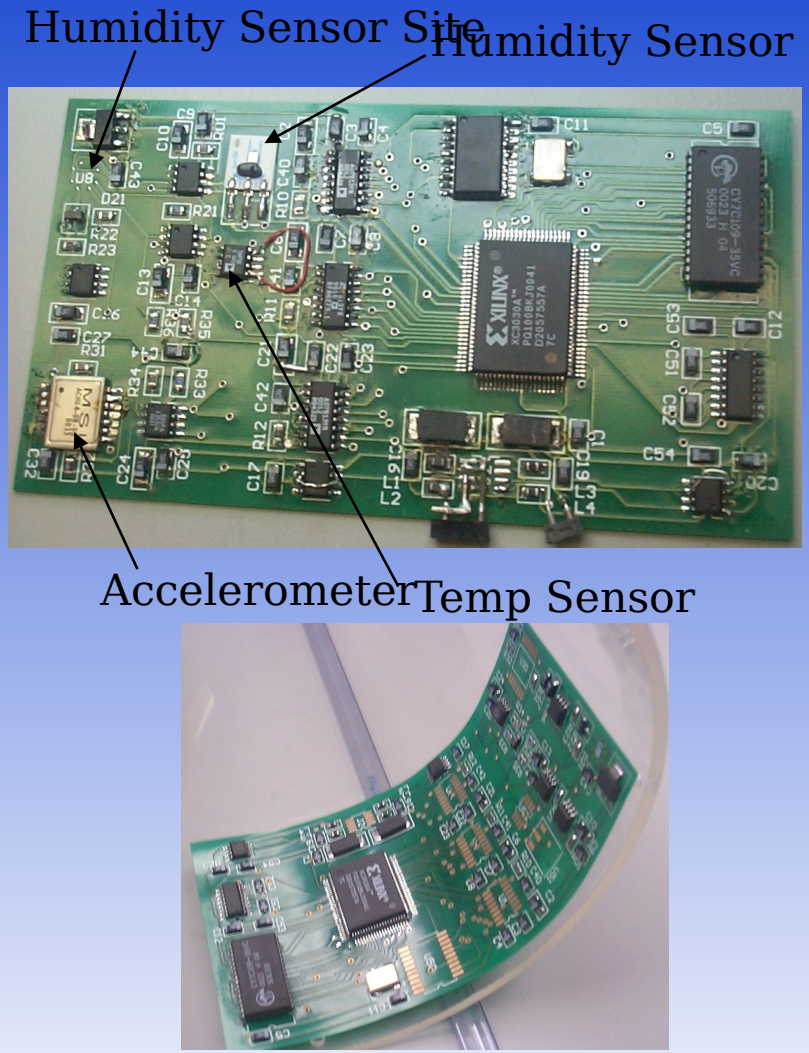
Assembled Systems



- Initial prototypes assembled on rigid and flex-circuits.
- Investigated system robustness and assembly into missile canister.
- Redesigned to yield smaller version for actual insertion.

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Current Status (PCB Version)

- Two sensor sets have been selected (one packaged and one unpackaged):
  - Humidity sensors - Hygrometrix HMX2000, Ohmic Instruments HC600
  - Temperature sensors - Hygrometrix HMX2000, Analog Devices TMP36
  - Vibration/Shock Sensors - Wilcoxon Research Accelerometer, Measurement Specialties ACH 04-08-05
- Chip-scale package designs developed, fabricated, and assembled with Hygrometrix and Wilcoxon sensor die using new die handling techniques. Initial characterization of sensor/package performed.
- Developed environmental monitoring system using surface mount COTS MEMS. Cost is ~$295 per board for 16 systems.
-

Item	Price		Item	Price		Item	Price		Item	Price
Sensors	$60		Electronic Components	$120		Boards	$27		Assembly	$90

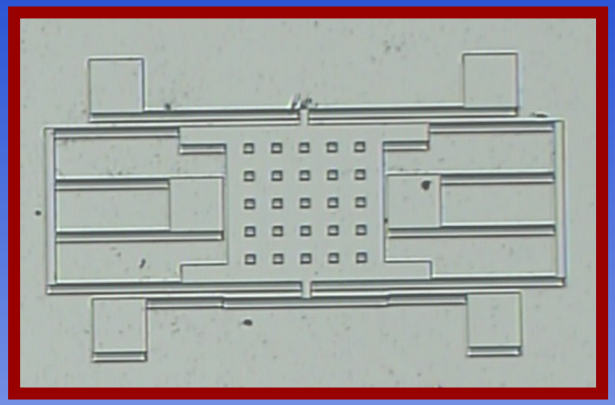
Functional testing and calibration complete for the packaged COTS set of sensors.

Future Work/Challenges

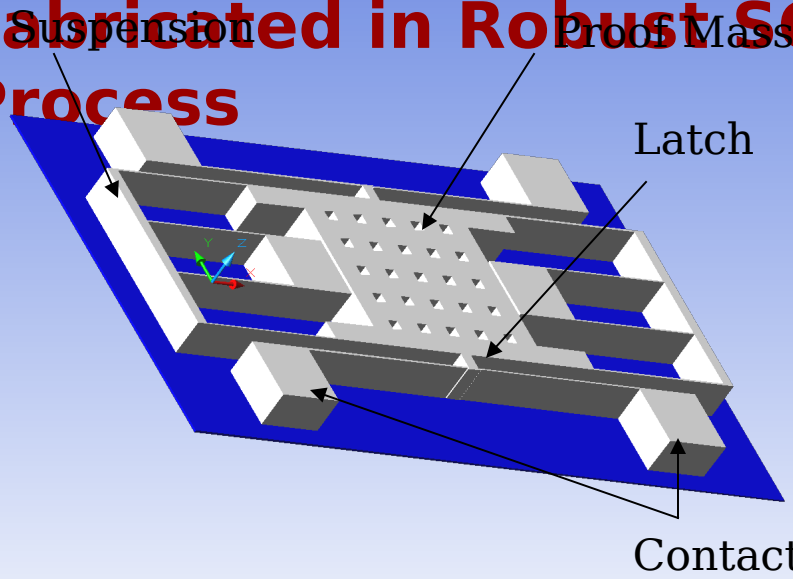
- Thorough characterization of the reliability and performance of the developed MEMS packaging techniques.
- Develop packaging and integration techniques for other environmental sensors (i.e. chemical, biological, etc.).
- Integrate the system on a flex circuit and characterize system reliability.
- Reduce system power consumption and size.
- Reduce system size through part count reduction, layout optimization, partial integration using MCM's/ASIMPS, and high-density PCB's

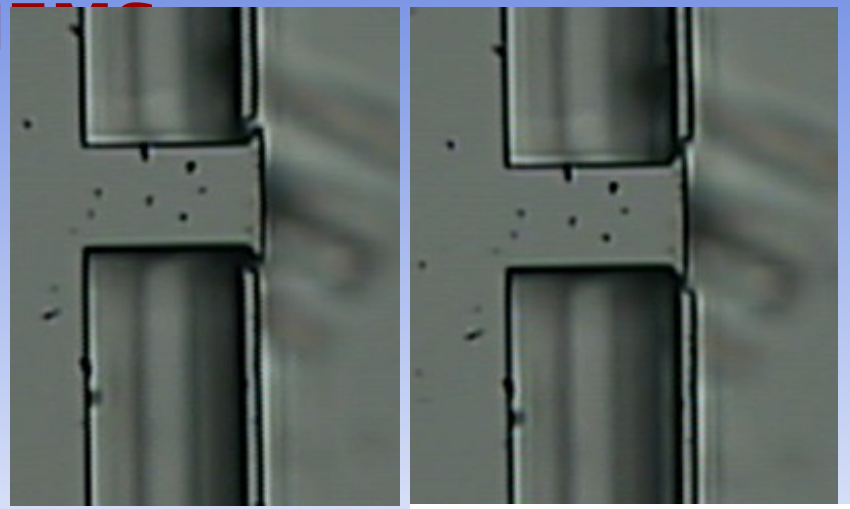
Latching accelerometers For Power reduction

- **No Standby Power Required**
- **Level Latching Shock Sensing**
- **Resetable**
- **Prototype Devices Fabricated in Robust SOI-MEMS Process**



Prototype Device





Off Latching Operation **On**

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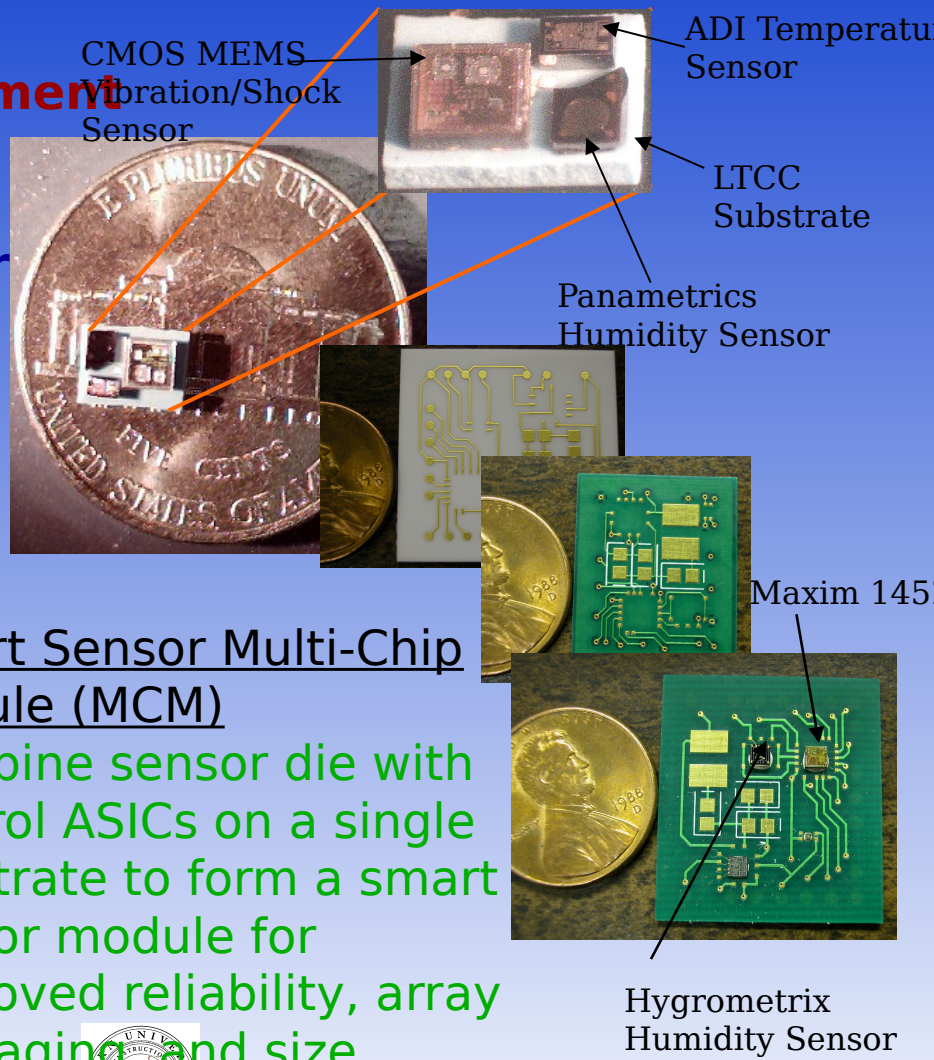
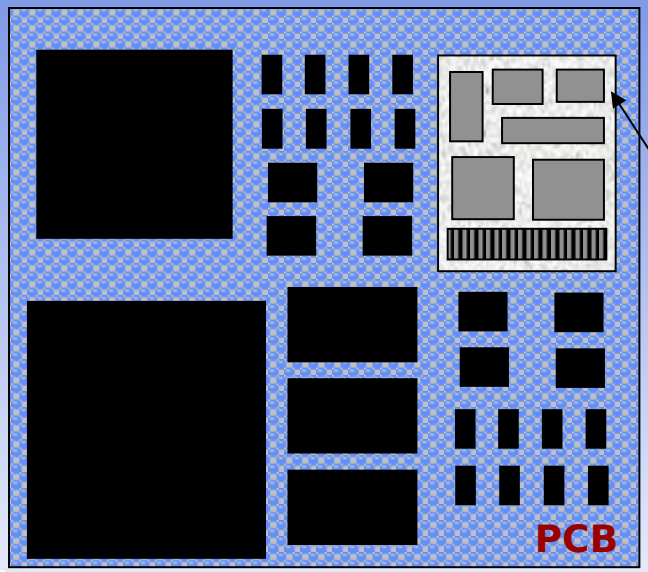
Multi-Chip Module Size reduction

- **Demonstration MCM in development**
  - MAXIM 1452 Sensor Interface
  - Temperature Sensor
  - Latching Shock Trigger Sensor
  - Vibration Sensor
  - Humidity Sensor
  - LTCC Substrate





Smart Sensor Multi-Chip Module (MCM)

Combine sensor die with control ASICs on a single substrate to form a smart sensor module for improved reliability, array packaging and size reduction

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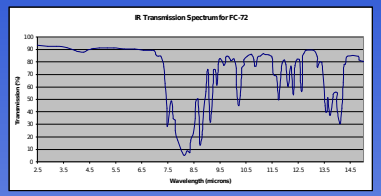
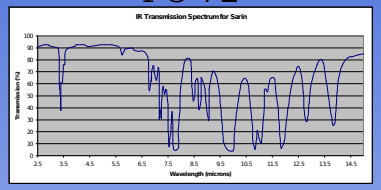
μOptics for Chemical Sensor Miniaturization

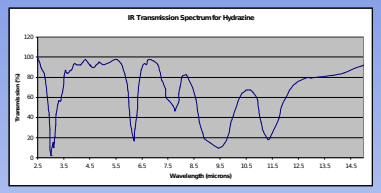
Spectral Responses of Interest



FC-72

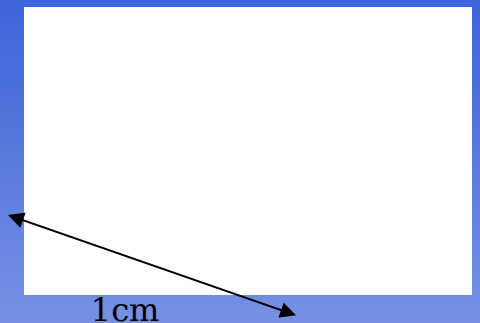


Sarin

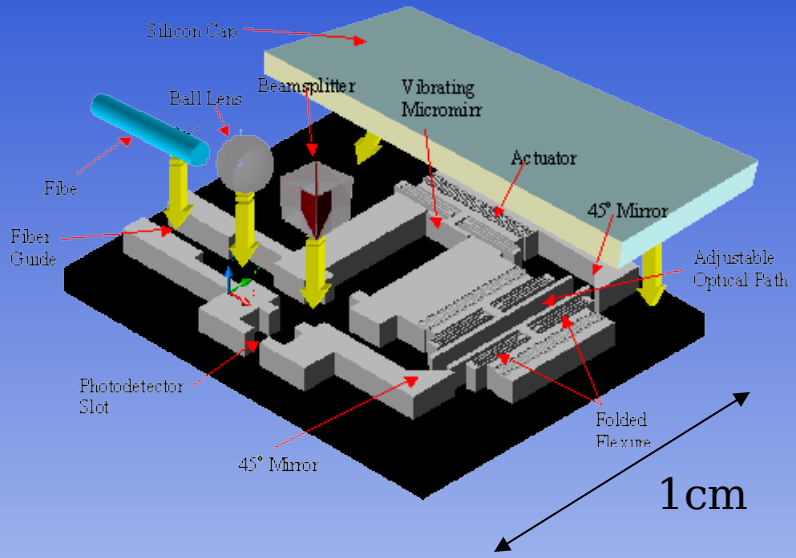


Hydrazine

Simulation of MEMS-based Optical Spectrometer

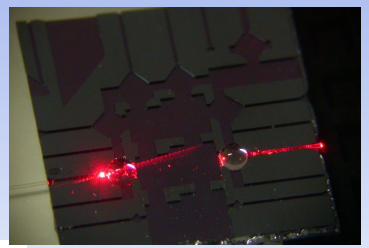


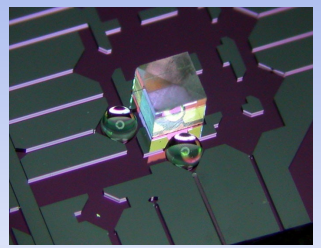
Micro Optics for Chemical Detection



Miniature Optical Components

Bringing Fiber & MEMS Together





Low cost, low power, miniature optical spectrometers & interferometers

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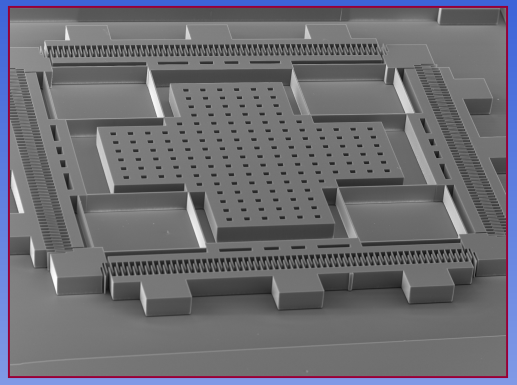
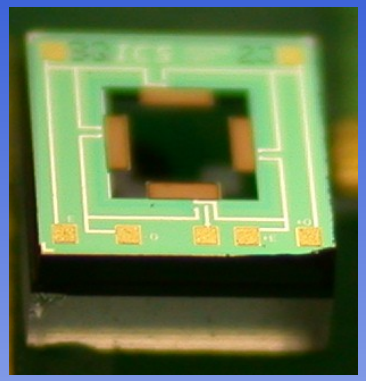
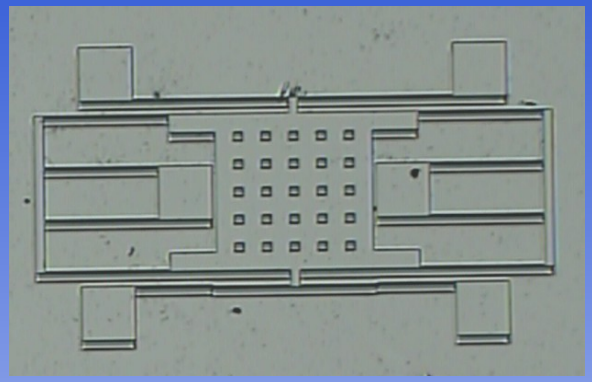
SOI-MEMS Based Sensor Suite-On-A-Chip



Existing 2-Axis SOI Accelerometer (Under Development)



Existing Silicon-Based Hygrometrix Humidity Sensor (Commercially Available)



SOI-Based Latching Shock Sensor (Under Development)

Sensor Suite-On-A-Chip

- **SOI-based 3-Axis MEMS Accelerometer**
- **SOI-based Latching Accelerometer**
- **Bulk etched Hygrometrix Humidity/Temperature Sensor**
- **CMOS Signal Conditioning ASIC**

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